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## Nonleptonic $\Lambda_b$ Decays at Colliders

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We discuss nonleptonic two-body decays of  $\Lambda_b$  baryons, which may be studied in the near future at colliders.

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## I. INTRODUCTION

Heavy baryons, i.e. bottom and charm baryons, are the simplest objects from the point of view of the heavy quark effective theory (HQET). In particular, for the  $\Lambda$  type baryons, in which the light degrees of freedom are coupled to spin zero, the additional symmetries of HQET give many interesting relations among weak transition form factors. In fact, since the two polarization directions of the heavy  $\Lambda$  baryon form a spin symmetry doublet, the symmetries of HQET relate form factors even for heavy to light transitions [1].

ARGUS and CLEO as well as a future  $B$  factory will not be able to access baryonic heavy to heavy transitions, since they will run on the  $\Upsilon(4s)$  resonance which is below the  $\Lambda_b \bar{\Lambda}_b$  threshold. Thus, experimental information on these processes will be obtained only from colliders at very high energy. First evidence for semileptonic  $\Lambda_b$  decays at LEP has been reported by two groups (ALEPH collaboration [2] and OPAL collaboration [3]) from the process  $Z_0 \rightarrow \bar{b}b \rightarrow \Lambda_b(\bar{\Lambda}_b) + \text{anything}$ . A further measurement of  $\Lambda_b$  baryons was reported by the UA1 collaboration [4] where the decay channel  $\Lambda_b \rightarrow \Lambda J/\Psi$  was used to obtain a mass determination of the  $\Lambda_b$ .

In the present note we discuss nonleptonic decays of heavy  $\Lambda$  baryons using HQET [5] and factorization. We focus mainly on Cabibbo allowed two body decays which may be easily identified in a collider environment. As in the case of heavy  $\Lambda$  semileptonic decays [6], we may use the nonleptonic decays to obtain information on the  $b$  quark polarization in the process  $Z_0 \rightarrow \bar{b}b$ . Furthermore, from the measurement of the decay  $\Lambda_b \rightarrow \Lambda J/\Psi$  we may obtain some information on the fragmentation process of a heavy quark.

Neglecting penguin contributions, the effective Hamiltonian for the decays under consideration is given by

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} V_{UD}^* \left[ C_1(m_b) (\bar{c}\gamma_\mu(1-\gamma_5)b) (\bar{D}\gamma^\mu(1-\gamma_5)U) \right. \\ \left. + C_2(m_b) (\bar{D}\gamma_\mu(1-\gamma_5)b) (\bar{c}\gamma^\mu(1-\gamma_5)U) \right], \quad (1)$$

where  $U, D$  are either  $c, s$  or  $u, d$ ,  $C_1(m_b)$  and  $C_2(m_b)$  are the QCD coefficients given by

$$C_1(m_b) = \frac{1}{2} \left[ \left( \frac{\alpha_s(m_b)}{\alpha_s(m_W)} \right)^{-6/23} + \left( \frac{\alpha_s(m_b)}{\alpha_s(m_W)} \right)^{12/23} \right], \quad (2)$$

$$C_2(m_b) = \frac{1}{2} \left[ \left( \frac{\alpha_s(m_b)}{\alpha_s(m_W)} \right)^{-6/23} - \left( \frac{\alpha_s(m_b)}{\alpha_s(m_W)} \right)^{12/23} \right], \quad (3)$$

$m_W$  is the mass of the  $W$  boson, and  $\alpha_s(\mu)$  is the running coupling of QCD. This effective Hamiltonian mediates the two classes of decays we shall investigate in some detail in this paper. The first class contains a  $\Lambda_c$  in the final state:  $\Lambda_b \rightarrow \Lambda_c X$  where  $X$  can be  $\pi, \rho$  for  $U, D = u, d$  or  $D_s, D_s^*$  for  $U, D = c, s$ . The second class contains a light baryon in the final state:  $\Lambda_b \rightarrow \Lambda Y$  or  $\Lambda_b \rightarrow n Z$ , where  $Y$  can be  $\eta_c, J/\Psi$  ( $U, D = c, s$ ) or  $D, D^*$  ( $U, D = u, d$ ).

To evaluate the matrix elements of the effective Hamiltonian we shall employ the factorization assumption. By Fierz rearrangement we rewrite the effective Hamiltonian in a form which is suitable for use of the factorization assumption. In either case both terms of the effective Hamiltonian contribute. In the first class we have

$$H_{eff}^{(1)} = \frac{G_F}{\sqrt{2}} V_{cb} V_{UD}^* \left( C_1(m_b) + \frac{1}{N_c} C_2(m_b) \right) \\ \times (\bar{c}\gamma_\mu(1-\gamma_5)b) (\bar{D}\gamma^\mu(1-\gamma_5)U), \quad (4)$$

while the second class is mediated by

$$H_{eff}^{(2)} = \frac{G_F}{\sqrt{2}} V_{cb} V_{UD}^* \left( C_2(m_b) + \frac{1}{N_c} C_1(m_b) \right) \\ \times (\bar{D}\gamma_\mu(1-\gamma_5)b) (\bar{c}\gamma^\mu(1-\gamma_5)U). \quad (5)$$

From mesonic nonleptonic decays it is known that the mesonic analogues of the first class are stable under QCD corrections and the decays are reasonably well described using factorization. However, the mesonic analogues of the second class are not stable under QCD corrections, since the two contributions almost cancel. This may be seen in the decay  $B \rightarrow K^{(*)} J/\Psi$  for which we have, after factorization

$$\langle J/\psi K^{(*)} | H_{eff} | B \rangle = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left( C_2(m_b) + \frac{1}{N_c} C_1(m_b) \right) \\ \langle J/\psi | (\bar{c}\gamma_\mu(1-\gamma_5)c) | 0 \rangle \\ \langle K^{(*)} | (\bar{s}\gamma^\mu(1-\gamma_5)b) | B \rangle. \quad (6)$$

The rate obtained from factorization is too small for  $N_c = 3$  while the limit  $N_c \rightarrow \infty$  gives a reasonable value. We shall assume that the situation is similar for baryons, and take the limit  $N_c \rightarrow \infty$  for the baryonic decays of the second type.

The paper is organized as follows. In the next section we present the expressions for the hadronic matrix elements, as well as the decay rates and the

polarization variables. In section 3 the first class of decays is investigated, while section 4 focuses on the second class. Finally we discuss our results with emphasis on collider experiments, and present our conclusions.

## II. HADRONIC MATRIX ELEMENTS AND DECAY RATES

As pointed out in the introduction we evaluate the matrix elements of the effective Hamiltonian using the factorization assumption. Thus, two types of hadronic matrix elements are needed. The first is a transition from a  $\Lambda_b$  to a final state baryon (heavy or light) and the second is a meson decay matrix element.

For the transition matrix element between the two baryons we employ HQET. The heavy to heavy matrix element needed for the first class of decays is described in terms of a single form factor,

$$\langle \Lambda_c(v') | (\bar{c}\gamma_\mu(1 - \gamma_5)b) | \Lambda_b(v) \rangle = F_1(v \cdot v') \bar{u}(v') \gamma_\mu (1 - \gamma_5) u(v). \quad (7)$$

Due to heavy quark symmetries the form factor  $F_1$  is normalized at the non-recoil point, with

$$F_1(v \cdot v' = 1) = 1. \quad (8)$$

In a two body decay this form factor is needed at a single kinematic point. Since one expects that the form factor decreases as  $v \cdot v'$  increases, we may obtain at least an upper bound for the rate.

The matrix element for a transition from a  $\Lambda_b$  to a light baryon (the second class of decays) is given in terms of two form factors:

$$\begin{aligned} \langle \Lambda(p) | (\bar{\ell}\gamma_\mu(1 - \gamma_5)b) | \Lambda_b(v) \rangle \\ = \bar{u}(p) [F_1(v \cdot p) + \not{p} F_2(v \cdot p)] \gamma_\mu (1 - \gamma_5) u(v). \end{aligned} \quad (9)$$

Finally the decay matrix elements of the mesons are needed. They are in general defined by

$$\langle P(k) | L_\mu | 0 \rangle = f_P k_\mu, \quad (10)$$

$$\langle V(k, \epsilon) | L_\mu | 0 \rangle = f_V m_V \epsilon_\mu, \quad (11)$$

where  $P$  denotes a pseudoscalar meson and  $V$  a vector meson with mass  $m_V$ . For the decay constants  $f_P$  and  $f_V$ , we use

$$f_\pi = 132 \text{ MeV}, \quad f_\rho = 210 \text{ MeV}, \quad (12)$$

$$f_D = f_{D^*} = f_{D_s} = f_{D_s^*} = 200 \text{ MeV}, \quad (13)$$

$$f_{J/\Psi} = f_{\eta_c} = 383 \text{ MeV}, \quad (14)$$

where the value for the decay constant of the  $D$  meson is taken from [7] and the value for the charmonium bound states is obtained from the electromagnetic width of the  $J/\Psi$ .

In terms of these matrix elements, we may write the decay rate of the  $\Lambda_b$  into a baryon and a pseudoscalar meson  $P$ , as [8]

$$\begin{aligned} \Gamma &= \Gamma_0 \left[ 1 + \alpha \mathbf{S}_{\Lambda_b} \cdot \hat{\mathbf{p}} \right], \\ \Gamma_0 &= \frac{G_F^2 F_1^2(v \cdot v') f_P^2 |V_{bc}|^2 |V_{UD}|^2 p}{8\pi m_{\Lambda_b}}, \\ D &= (E + m) A^2 + (E - m) B^2, \\ \alpha &= -2ABp/D, \end{aligned} \quad (15)$$

where  $\mathbf{S}_{\Lambda_b}$  is the spin of the  $\Lambda_b$  in its rest frame and  $\hat{\mathbf{p}}$  is a unit vector in the direction of motion of the  $\Lambda_c$  again in the rest frame of the  $\Lambda_b$ . This form is valid if the polarization of the daughter baryon is not measured.  $E$  and  $m$  are the energy and mass of the daughter baryon, respectively.

The quantities  $A$  and  $B$  depend on the particular decay being treated. For a decay of the type  $\Lambda_b \rightarrow \Lambda_c P$ ,

$$A = m_{\Lambda_b} - m_{\Lambda_c}, \quad B = m_{\Lambda_b} + m_{\Lambda_c}, \quad (16)$$

while for the decay  $\Lambda_b \rightarrow \Lambda P$ ,

$$\begin{aligned} A &= m_{\Lambda_b} - m_\Lambda + r(m_{\Lambda_b} + m_\Lambda - 2E_\Lambda), \\ B &= m_{\Lambda_b} + m_\Lambda - r(m_{\Lambda_b} - m_\Lambda - 2E_\Lambda), \\ r &= F_2(v \cdot p)/F_1(v \cdot p). \end{aligned} \quad (17)$$

Similarly, for the decays involving a vector meson  $V$ , we may write the decay rate in the same form as eqn. (15), but now

$$\begin{aligned} \Gamma_0 &= \frac{E_V^2}{m_V^2} DY, \\ \alpha &= 2 \left[ ap(1 + bp^2) + \frac{2m_V^2 cp}{E_V^2} \right] / D, \\ D &= a^2 p^2 + (1 + bp^2)^2 + \frac{2m_V^2}{E_V^2} (1 + c^2 p^2), \\ Y &= \frac{G_F^2 F_1^2(v \cdot v') f_V^2 m_V^2 |V_{bc}|^2 |V_{UD}|^2 p (E + m)}{16\pi m_{\Lambda_b}}. \end{aligned} \quad (18)$$

For the decay  $\Lambda_b \rightarrow \Lambda_c V$ ,

$$a = -\frac{m_{\Lambda_b} + m_{\Lambda_c}}{E_V(E_{\Lambda_c} + m_{\Lambda_c})}, \quad b = \frac{1}{E_V(E_{\Lambda_c} + m_{\Lambda_c})}, \quad c = \frac{1}{E_{\Lambda_c} + m_{\Lambda_c}}, \quad (19)$$

while for the decay  $\Lambda_b \rightarrow \Lambda V$ ,

$$\begin{aligned} a &= -\frac{(1+r)(m_{\Lambda_b} + m_{\Lambda}) - 2rE_V}{(1+r)E_V(E_{\Lambda} + m_{\Lambda})}, \\ b &= \frac{1-r}{(1+r)E_V(E_{\Lambda} + m_{\Lambda})}, \\ c &= \frac{1}{(1+r)(E_{\Lambda} + m_{\Lambda})}. \end{aligned} \quad (20)$$

### III. THE DECAYS $\Lambda_B \rightarrow \Lambda_C X$

The total rates are important for estimating the integrated luminosity needed to obtain a signal, while the initial state polarization is an interesting issue at the  $Z_0$  resonance. The  $b$  quarks originating from a  $Z_0$  decay are polarized to a very high degree (94%). Furthermore, in the heavy quark limit the spin of the heavy quark decouples and, since the spin of the  $b$  quark is that of the  $\Lambda_b$ , one may access the polarization of the  $b$  quark via the polarization of the  $\Lambda_b$ . This has already been suggested for the case of  $\Lambda_b$  semileptonic decays [6] and in the present note we extend this discussion to nonleptonic decays.

From HQET the normalization of the form factor  $F_1$  (eqn. (7)) at the non-recoil point  $v \cdot v' = 1$  is known. In addition, we have in the kinematic region relevant for the decay that  $|F_1(v \cdot v')| < 1$ . We do not know the kinematic dependence of the form factors from first principles, but we may still give upper limits for the rates by setting  $F_1 = 1$  in the equation for the total rate.

Table I contains our results for the branching fractions and for the polarization variables. The values for the total rates were previously presented in [8] from specific parametrizations of the form factor, and the errors are estimated from using three different parametrizations. In addition, we also give the upper limit on the total rates obtained from setting  $F_1(v \cdot v') = 1$ .

### IV. THE DECAYS $\Lambda_B \rightarrow \Lambda Y$ AND $\Lambda_B \rightarrow n Z$

From eqns. (15), (17), (18) and (20), we may obtain the rates and the polarization variables for the decays  $\Lambda_b \rightarrow \Lambda Y$  and  $\Lambda_b \rightarrow n Z$  as a functions of the ratio  $r$  and form factor  $F_1(v \cdot v')$ . However, while the polarization variable is independent of the form factor  $F_1$ , the absolute rate is not. HQET gives us no

information on this form factor, and one would have to rely on a different approach, such as explicit model construction. Instead, in what follows, we present upper limits for the absolute rates by setting  $F_1(v \cdot v') = 1$ . This provides an upper limit since the form factor is, in essence, a wave function overlap taken between the parent and daughter baryon, and this should be less than unity in all regions of physically accessible phase space.

Since neutrons are notoriously difficult to detect, we present results for the  $\Lambda_b \rightarrow \Lambda J/\Psi$  and  $\Lambda_b \rightarrow \Lambda \eta_c$  channels only, and begin with the latter channel. In the range  $|r| \leq 1$ ,  $\alpha$  for the  $\Lambda_b \rightarrow \Lambda \eta_c$  channel is predicted to have the values  $-1.0 \leq \alpha \leq -0.8$ , and is shown as one of the curves in fig. 1. While this suggests that some polarization information may be extracted from this decay mode, the  $\eta_c$  lacks any distinctive signal that allows it to be easily identified. From fig. 2, we see what the upper limits on the branching fraction into this decay channel look like as a function of  $r$ .

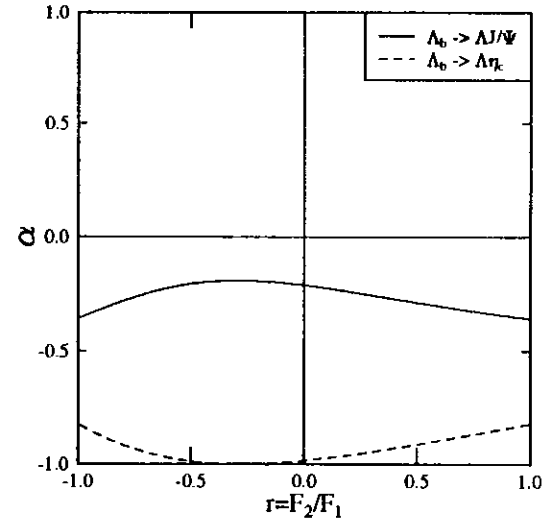


Figure 1: The polarization variable  $\alpha$  as a function of the ratio  $F_2(v \cdot v')/F_1(v \cdot v')$ , for the processes  $\Lambda_b \rightarrow \Lambda J/\Psi$  and  $\Lambda_b \rightarrow \Lambda \eta_c$ .

In the  $\Lambda_b \rightarrow \Lambda J/\Psi$  channel, the polarization variable  $\alpha$  is also shown in fig. 1, and the upper limits on the branching fraction are shown in fig. 2. At  $r = 1$ , corresponding to  $F_1 = F_2 = 1$ , we obtain a branching fraction of 1.2%. We

emphasize that we expect that  $F_1$  should be less than unity, and for the decays we consider, perhaps significantly so. A conservative guess for the value of  $F_1$  would make our 'prediction' for the branching fraction in this channel of the order of 0.1% - 0.3%. This would therefore cast some doubt on recent UA1 claims that the branching fraction in the  $\Lambda_b \rightarrow \Lambda J/\Psi$  channel is  $1.8 \pm 1.1\%$  [4], and would at least suggest that the true value lies near the lower end of the range given by the experimental uncertainty.

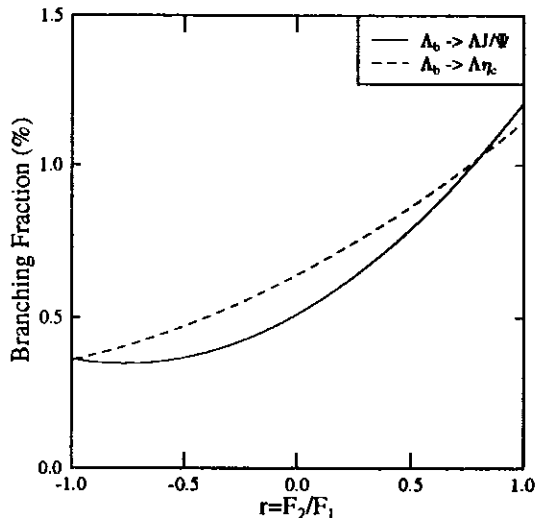


Figure 2: Upper limits on the branching fractions for the processes  $\Lambda_b \rightarrow \Lambda J/\Psi$  and  $\Lambda_b \rightarrow \Lambda \eta_c$ , as functions of the ratio  $F_2(v \cdot v')/F_1(v \cdot v')$ .

Of course, our estimates are based on some assumptions in addition to HQET. Not much may be said about the factorization assumption, but we have also approximated the QCD coefficient for the second class of decays by its  $N_c \rightarrow \infty$  limit. This turns out to be a successful description for the mesonic systems, and we have assumed this limit to be reasonable for the baryonic decays as well. However, even if the limit  $N_c \rightarrow \infty$  does not give an appropriate description for the baryons, the absolute value for the QCD coefficient for  $N_c = 3$  is smaller than for  $N_c \rightarrow \infty$ ; this would reduce the cross sections by about an order of magnitude, making the UA1 measurement even more improbable.

## V. DISCUSSION AND CONCLUSIONS

The  $\Lambda_b$  baryons we discuss here originate from the fragmentation of a high energy  $b$  quark, which is created either from a  $Z_0$  decay for the case of LEP, or from boson-gluon fusion for the case of HERA or a hadron collider. Little is known about the fragmentation process; based on assumptions which are usually made for Monte Carlo simulations we assume that ten percent of the  $b$  quarks created fragment into heavy baryons. Furthermore, we assume that the  $\Lambda_b$  baryon is the only bottom baryon decaying weakly. A possible exception could be the  $\Omega_b = ssb$  but we ignore this possibility for the moment, since we are only attempting to obtain an estimate.

The first class of decays involves a  $\Lambda_c$  in the final state which needs to be reconstructed in order to pin down the corresponding two-particle decay of the  $\Lambda_b$ . Since the two-particle decays of the  $\Lambda_c$  that are easy to identify have branching fractions in the percent region this may be a difficult task.

A sample of  $10^6$   $Z_0$  decays at LEP should contain about  $1.5 \cdot 10^5$  decays of the type  $Z_0 \rightarrow b\bar{b}$ . From these there should be about  $1.5 \cdot 10^4$  events involving a  $\Lambda_b$ . Thus one expects for the channels  $\Lambda_b \rightarrow \Lambda_c \pi$  and  $\Lambda_b \rightarrow \Lambda_c \rho$  between 50 and 100 events in  $10^6$   $Z_0$  decays. This number is certainly reduced by a large factor due to reconstruction efficiencies for the  $\Lambda_c$  with the result that this channel may be difficult to access. The branching fractions for channels involving charmed strange mesons are a factor of five larger so that these channels may be better candidates for observation in present LEP data.

As mentioned above the  $\eta_c$  will be difficult to detect and hence we focus on the channel  $\Lambda_b \rightarrow \Lambda J/\Psi$  which has a clean signature. However, with a branching fraction of 0.1% - 0.3% one expects only 4 events in a sample of  $10^6$   $Z_0$  decays. In addition, this number has to be multiplied by the branching fractions for  $J/\Psi \rightarrow \mu^+ \mu^-$ , as well as that for  $\Lambda \rightarrow p \pi$ . We would therefore expect this channel not to be observable in present LEP data. As pointed out previously the branching fraction for  $\Lambda_b \rightarrow \Lambda J/\Psi$  measured by UA1 is about an order of magnitude larger than our estimate. However, even if this branching fraction is as large as claimed, this decay channel may still be difficult to detect in the present LEP data sample.

At HERA one expects about  $10^6$   $b$  quarks to be produced per year from boson-gluon fusion, a number that is slightly larger than for LEP. With a fragmentation probability for  $b \rightarrow \Lambda_b$  of 10%, this corresponds to  $10^5$  events involving  $\Lambda_b$  baryons. However, the signal to background ratio for the detection of  $b$  quarks at HERA is about three orders of magnitude worse than at LEP, which effectively nullifies any possible gain from the larger number of  $\Lambda_b$ 's.

Finally, another source for  $b$  quarks is the Fermilab collider. Since this is

a hadron hadron collider the main process for heavy quark production is gluon gluon fusion. The production cross section for  $b$  quarks is very large, about a factor of 4000 larger than the corresponding cross section at HERA, namely about  $40 \mu\text{barns}$ . In the 88/89 runs CDF collected about  $4.1 \text{ pb}^{-1}$  of integrated luminosity which corresponds to about  $10^8$   $b$  quarks, which in turn would yield about  $10^7$   $\Lambda_b$  baryons. However, this data sample can not be used in a manner comparable to the LEP analysis, since very good vertex detection is needed. The upcoming upgrade of CDF will open up  $b$  physics opportunities at the Tevatron.

The  $b$  quarks originating from the decays of a  $Z_0$  will be 94% polarized. As pointed out above this polarization will translate into a corresponding polarization of the  $\Lambda_b$ . Boosting back into the rest frame of the  $\Lambda_b$  baryon the measured angular distribution of the decay products is given by

$$\Gamma = \Gamma_0(1 + \mathcal{P}\alpha S_{\Lambda_b} \cdot \hat{p}) \quad (21)$$

where  $\mathcal{P} = -0.94$  is the polarization predicted by the standard model. In particular for the decays  $\Lambda_b \rightarrow \Lambda_c P$  the polarization variable  $\alpha$  is predicted to be minus one so that one could try to measure  $\mathcal{P}$  from the angular distribution of the decay products.

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# TABLES

TABLE I. Predictions for the decays  $\Lambda_b \rightarrow \Lambda_c P$  and  $\Lambda_b \rightarrow \Lambda_c V$ . All rates are expressed as branching fractions, in percent.

Channel	$\alpha$	$\Gamma$	$\Gamma_{max}$
$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$	-1.000	$0.46^{+0.2}_{-0.31} \%$	2.0%
$\Lambda_b \rightarrow \Lambda_c^+ D_s^-$	-0.991	$2.3^{+0.30}_{-0.40} \%$	6.5%
$\Lambda_b \rightarrow \Lambda_c^+ \rho^-$	-0.903	$0.66^{+0.24}_{-0.40} \%$	2.5%
$\Lambda_b \rightarrow \Lambda_c^+ D_s^{*-}$	-0.437	$1.73^{+0.20}_{-0.30} \%$	4.7%